AERODYNAMIC CONTROL OF LONG-SPAN SUSPENSION BRIDGES

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Summary We study the aerodynamic control of long-span suspension bridges and seek to raise the critical flutter wind speeds, while simultaneously suppress buffeting. The control system design study is based on a sectional bridge model. A streamlined bridge deck is assumed and non-steady thin aerofoil theory is used to describe the interactions between the bridge deck and the (constant-velocity) air stream. While a wide variety of control systems is possible, we focus on a compensation scheme that can be implemented using passive mechanical components such as springs, dampers and a rack and pinion mechanism. A single-loop control system is investigated that controls a trailing-edge flap by sensing movements of the bridge deck; several such mechanisms are contemplated. The main result is that critical flutter speed can be improved while simultaneously suppressing buffeting by using the same passive mechanical controller.

INTRODUCTION

No problem in the field of civil-engineering-related aeroelastic instabilities has received the publicity afforded the collapse of the Tacoma Narrows Bridge that occurred during November of 1940. Apart from capturing the public imagination, this disaster triggered the development of modern bridge aeroelasticity and marked the beginning of the quantitative study of bridge aerodynamics. The aim of this paper is to use control means to increase the critical wind speed associated with flutter and suppress the bridge structure's buffet response. The control method we will study is illustrated in the left-hand

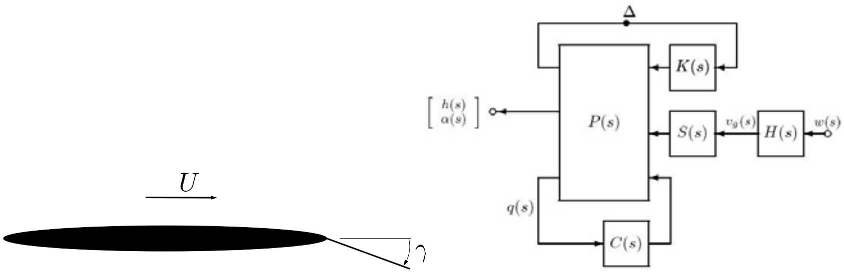

Figure 1. The right-hand figure is the idealized cross section of a long-span suspension bridge with a controllable trailing-edge flap. The wind speed is denoted U. The right-hand figure represents the block diagram of the aerodynamic control system.

figure of Figure 1 and makes use of a controllable trailing-edge flap that will be manipulated by feedback.

The right-hand figure of Figure 1 shows how the various elements of the control scheme are brought together. The dynamics of the bridge and non-circulatory fluid mechanics are represented by $P(s)$. The trailing-edge flap is controlled using a passive controller $K(s)$ that is responsive in our study to the heave motion of the flap hinge. The vertical component of the wind velocity gust disturbance $v_g(s)$ is modelled as a unit-variance white noise process $w(s)$ that is fed into a colouring filter $H(s)$. The filter transfer function is a stable minimum-phase spectral factor of a rational approximation to the (vertical) von Kármán turbulence spectrum. The vertical gust velocity is converted into the corresponding buffet force by the rational approximation $S(s)$ of the Sears function. As has been explained elsewhere [1], the Theodorsen circulation function approximation is given by C(s), with the lift-producing signal $q(s)$ indicative of the vertical velocity of the air stream relative to the structure. The bridge deck's heave and pitch response are given by $h(s)$ and $\alpha(s)$ respectively. Because of page limitation, we omit the structure and dynamic models, which can be found in [1]. We use Akashi Kaikyo suspension bridge section as working example, see Table 1 of [1] for its parameters. In Figure 8 of [1], we show a root-locus for the open-loop system of this bridge section, from which it is clear that pitch-mode flutter occurs at a wind speed of 52 m/s, while the torsional divergence mode goes unstable at 70 m/s . We aim to increase the critical wind speed for flutter to match that for torsional divergence using the control system.

CONTROLLER DESIGN AND RESULTS

In the context of large civil engineering structures, many advantages derive from the use of passive controllers that require no power supply. The class of mechanical controllers we are considering in this papers is illustrated in Figure 2, where the bridge's heave is h, the deck pitch angle is α, the flap angle is γ and the aerodynamic moment is M^{γ}. The control system is made up of several components including a pinion attached to the flap and mounted on the bridge deck. The pinion is driven by a rack that is attached to a passive mechanical network with admittance functions $Y(s)$. Depending on

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the details relating to any particular bridge structure, it might be necessary to make use of a compensation network anchor point that is attached to some large, but compliant structure. As shown in Figure 2, structural compliance will manifest as a spring (with stiffness K_s; here we let $K_s = 1500N/m$.). As is evident from Figure 2, the control flap is actuated by $Y(s)$ and the rack and pinion arrangement as the deck moves. The network through-variable associated with $Y(s)$ is the compressive force $F(t)$, while its across-variable is the velocity $\dot{x}(t)$. If $Y(s)$ is passive, then $K(s)$ is passive. It is easy to see that $M^c = K(s)x(s) = srY(s)x(s)$.

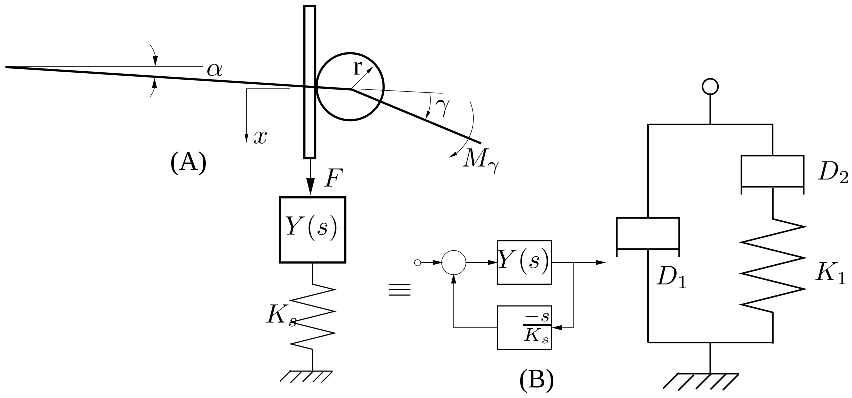

Figure 2. Mechanical network for flap control with flexible structural mounting. Illustrated in Figure (A) is a conceptual passive controller in which flap-hinge heave is used to control the control flap. Figure (B) is a feedback representation of the series spring-controller connection. The right-hand figure is the realization of a first-order mechanical lag compensator.

The control system design will focus on the optimization of $Y(s)$. The selected performance criterion is to minimize the power in the deck's heave and pitch responses due to wind turbulence, i.e., minimizing the $\mathcal{H}_2$ norm of the closed-loop transfer function $H(s,p)$ for the system in the right-hand figure of Figure 1 that maps the unit variance white noise w to $[h,\ \xi\alpha]^T$ for a wind speed of 60 m/s. The constant ξ is used to weight the relative importance of the heave and pitch responses; a value of $\xi = 40$ is used throughout. To ensure that the optimization problem is well posed, we impose the four constraints: a closed-loop stability constraint, a flap-length constraint ($\leqq 2.5$ m), network passivity, and robust stability constraint. We use a first-order passive compensator of the form $Y(s) = k\,\frac{s+z_0}{s+p_0}$, where k, z_0 and p_0 are constrained to be non-negative to ensure passivity. The hard constraints were checked at wind speeds of 5 m/s to 70 m/s in steps of 5 m/s. The optimal compensator network found by the MATLAB sequential quadratic programming algorithm FMINCON was: $k = 944.4320, z_0 = 1.4, p_0 = 0.1, r = 1.25$ with an optimal flap chords of 2.5 m. A physical realization of $Y(s)$ can be found in the right-hand figure of Figure 2.

Time response Figures 3 shows a marked reduction in both the heave and pitch response due to buffeting, with angular perturbations of the flap relatively modest. A small flap response is important so that low levels of flow separation are ensured. Because of page limitation, we omit root locus diagram, Nyquist diagram and $\mathcal{H}_2$-norm diagram, which can be found in Figures 17 and 18 of [1]. We also omit the time simulation for higher wind speed.

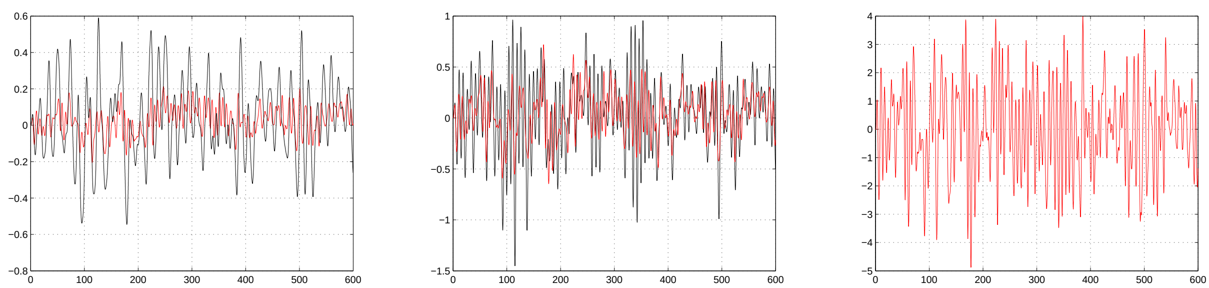

Figure 3. Time simulations (in seconds) showing the mixed robustness $\mathcal{H}_2$ buffet suppression scheme for U=35 m/s. The left-hand figure shows the open-loop (black) and the closed-loop (red) heave responses (in metres). The centre figure shows the open-loop (black) and the closed-loop (red) pitch responses (in degrees). The right-hand figure shows the closed-loop flap angle response (in degrees).

References

[1] D. J. N. Limebeer, J. M. R. Graham, and X. Zhao, "Buffet suppression in long-span suspension bridges," *Annual Reviews in Control*, vol. 35, pp. 235–246, 2011.